PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
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Invited Review

Photovoltaic Systems: An End-of-Millennium Review

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The production of electricity from photovoltaics continues to attract worldwide interest, most recently as a power source for distributed energy generation. Today's photovoltaic systems are already being used effectively for smaller power needs in remote applications. For both of these applications, the issues of reliability, efficiency, safety, and low cost are the principal drivers of system technology. This review uses these design issues to provide a system perspective on the current status of the technology, the changes it has already experienced and the necessity for improvements, especially in tomorrow's systems. The discussion of remaining issues focuses on the reduction of area-related and collector costs, the accurate prediction of performance and lifetime, and the need for developing much better information on recurring costs for maintenance and component replacement. Copyright © 1999 John Wiley & Sons, Ltd. This paper was produced under the auspices of the US Government and it is therefore not subject to copyright in the US.

INTRODUCTION

Over the past two decades, photovoltaic systems have undergone a number of significant changes. While the installation of systems worldwide has increased to a capacity in excess of 500 MW, real installed system costs have decreased by an order of magnitude. New technology system components such as sine wave inverters, valve-regulated batteries, and microprocessor-based controls are commonplace in today's photovoltaic systems. Reliability concerns have ceased to be an issue for high-quality photovoltaic collectors with long-term warranties. On the other hand, many aspects of system technology have remained relatively constant. Crystalline silicon collectors continue to dominate the marketplace and the marketplace continues to be dominated by off-grid, remote power applications including water pumping, telecommunications, and small facility power.

Although the future of photovoltaic systems promises to be excellent, a number of technical and economic issues that may limit acceptance and use of the technology have yet to be resolved. This review addresses many of these issues within the context of specific and basic questions that have been and probably will continue to be raised concerning photovoltaic systems. These questions have been used as sections in the review and are listed below:

- How much do photovoltaic systems cost?

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- What might happen to system costs in the future?
- What are the basics of system performance and design?
- How long does a photovoltaic system work?
- What must be done to maintain a photovoltaic system?
- Are photovoltaic systems safe to use?
- How does photovoltaics work in hybrid systems?
- How do customers feel about their systems and what is needed for more systems to be purchased?

At the conclusion of the paper we use the same questions to provide the perspective presented in the review. The scope of this review is focused on examples from the United States that are applicable to system issues worldwide.

BACKGROUND

The question of what photovoltaic systems can be used for is the easiest to address. Virtually any electrical load can be met with a photovoltaic power system, realizing each system may have specific requirements. For example, alternating current loads require an inverter. Grid-tied loads require synchronous operation with the grid. Energy storage (batteries) may be required. But there are no technical reasons that preclude photovoltaics from generating electricity for any load, given that sufficient physical area for collectors, solar access, and money are available for the application.

Photovoltaic technology is being used in many terrestrial electric power systems, primarily in one of two ways based upon similarities in operation and design. One is in systems that stand alone, where photovoltaics generate all of the on-site electricity needs. The other is when photovoltaics is one of two or more sources of electricity. The role for photovoltaics in these two types of systems is very different, and the design decisions and performance requirements are very different as well.

Applications that fall into the 'all photovoltaic electric power system' category can be both ac and dc, and may or may not have some sort of storage. The design of these stand-alone systems requires that the photovoltaics generate enough electricity to supply 100% of the electrical energy at the site. Water pumping, data collection and telemetry, signing, ventilation fans, battery charging, vaccine refrigerators and area lighting are typical applications that fall into the stand-alone category. For these systems to work predictably, the designer must know

(1) how much power is needed per unit of time by the electrical load and the duty cycle, and how that will change in time;
(2) how the efficiency is affected by changes in electrical input to the load;
(3) how much power is available from the sun at the site;
(4) how environmental changes will affect the performance and reliability of the system components and the load;
(5) how to select components and prescribe technical specifications for subsystems; and
(6) the magnitude of the losses in the proposed design and aging of the system components.

In the other type of system, where photovoltaics is providing only a fraction of the overall energy required, the requirements on photovoltaics are reduced, but most of the design concerns remain. In these systems, the electrical grid, a wind generator, and/or, most commonly for remote power systems, an engine generator is the other source. Grid-tied systems as well as hybrids fall into this grouping. In these cases, it is the control subsystems and interfaces that become paramount, not the generating capacity of the photovoltaics.

Because there is uncertainty in many of these areas, and because these are elements that will change over the lifetime of the power system, there will always be design and performance issues surrounding power system design, including photovoltaic systems, for dedicated loads. Although there is general agreement on some of the system design and performance requirements, many important issues are still unresolved. What we have done is to look at various issues and provide answers where we can provide specific examples and references.

HOW MUCH DO PHOTOVOLTAIC SYSTEMS COST?

The lowest documented price[1] for grid-tied systems in the US as of 1998 is $5.07/W producing electricity consistent with levelized energy costs between $0.15 and 0.20/kWh. These systems contain no battery storage, are mounted on residential roofs, and are the result of a focused plan by the utility owner to aggressively reduce costs through creative procurement actions, subsidies, and long-term hardware supply contracts. A typical 4-kW residential system, one of over 400 systems installed by the Sacramento Municipal Utility District's (SMUD) Pioneer program, is shown in Figure 1. Other documented grid-tied system costs in the US, as well as other countries, show higher numbers that vary widely.

The Utility Photovoltaic Group (UPVG), which is the cornerstone of the photovoltaic commercialization effort for grid-tied systems in the US, just made 14 contract awards[2] that will result in the installation of 2·9 MW at a cost of $2,900,000, or $10.00/W. Even with low-cost money and small returns required on investment, these systems will provide electricity at $0.25–$0.30/kWh and upwards. Commercialization efforts in the US are similar to those elsewhere in the world, whereby grid-tied systems are subsidized by government grants/buy-downs, as well as by utilities and their customers, to make up for the higher costs. The information[3] in Table I shows costs from around the globe that are consistent with recent cost information in the US.

A significant problem is created when grid-tied costs are applied erroneously to stand-alone photovoltaic and hybrid systems. Many of these latter systems require batteries, back-up generators, as well as control systems and are installed in remote areas where access is difficult and expensive.

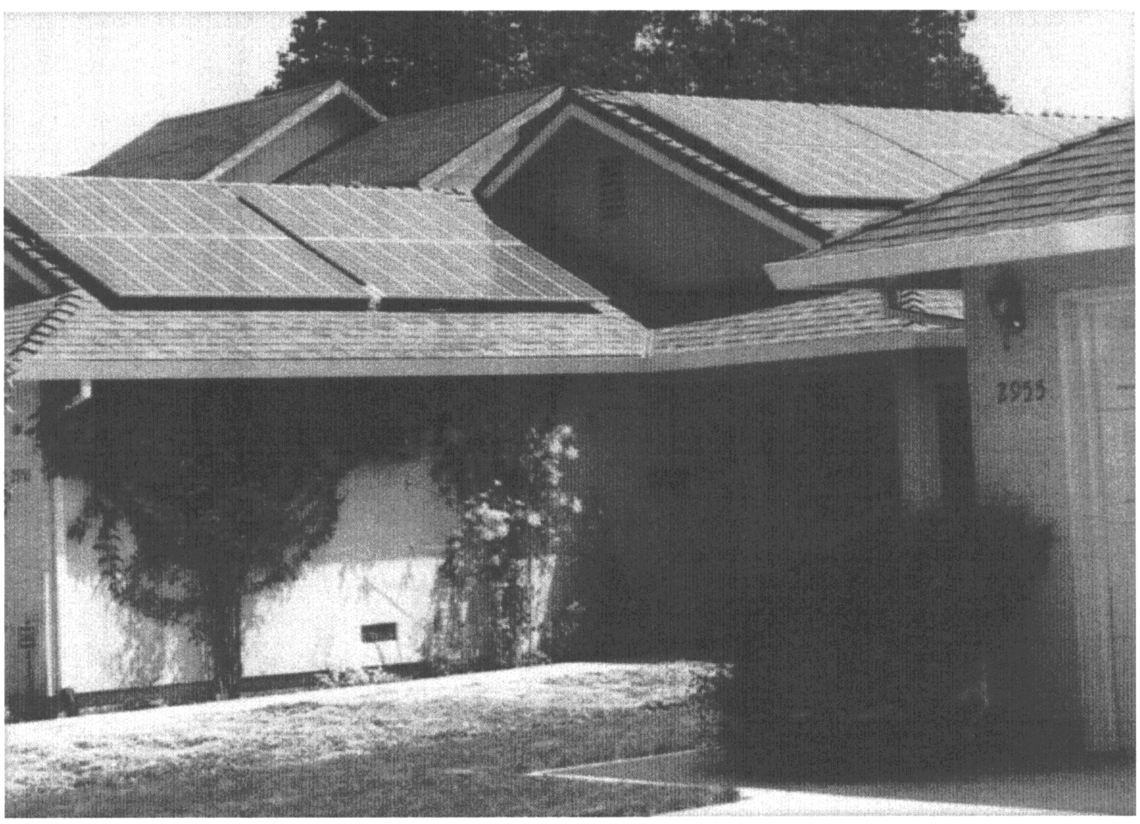

Figure 1. SMUD 4-kW residential system

Table I. Cost (as of 1996) vs size for various photovoltaic applications in USD/Wp

Country	Off-grid 100–500 Wp	Off-grid 1–4 kWp	On-grid 1–4 kWp	On-grid 10–50 kWp	On-grid > 50 kWp
Canada	14	10·7	—	—	—
Germany	27·6	11·4	7·3	9·2	8·5
Italy	16·5	15	12·6	10·7	7–10
Japan	—	—	15	20	—
US	15–20	10–12	6·9–10·1	9–14·5	12–13·7
All countries	14–41	10–28	6·9–20	7·5–30	7–13·7

Table II. Cost vs size for recently installed hybrid systems in the US

Site	Size (kWp)	Installed price ($/Wp)
Dangling Rope Marina, Glen Canyon	115	11·77
Cottonwood, Joshua Tree National Park	20	13·50
Chaparral, Pinnacles National Monument	9·6	14·06
Santa Cruz Island, Channel Islands	140	15·00
Visitor Center, Fort Craig	2	22·50
Visitor Center, Mojave National Preserve	4·2	25·24
Hole-in-the-Wall, Kings Canyon	8	13·12
North Manitou Island, Sleeping Bear Dunes	11·2	13·75

A cost survey of recently installed hybrid photovoltaic–engine systems (Table II) shows that the prices for these systems have the same wide variation as for grid-tied systems, ranging from approximately $12.00/W to well over $20.00/W. Many potential photovoltaic system users are confused when they are exposed to such a wide range of prices, especially when they assume that $6.00–7.00/W is a reference value for any kind of photovoltaic system.

Off-grid photovoltaic systems are economic worldwide and represent more than 75% of the market. These systems, such as the hybrid facility power system at North Manitou Island in Sleeping Bear Dunes National Lakeshore, Michigan (Figure 2) are competing with engine-powered generators, primary batteries, and other remote power options where the cost is usually 3–4 times greater than typical costs for grid-supplied electricity. Over the last 10 years, system prices reflect this remote market demand and the price of competitive technologies.

WHAT MIGHT HAPPEN TO SYSTEM COSTS IN THE FUTURE?

This question has several possible answers and requires discussion from several points of view. Let's look at what has happened over the past two decades.

Beginning in the late 1970s and early 1980s, the US Photovoltaics Program awarded competitive contracts to a number of system suppliers for the installation of flat-plate and concentrator photovoltaic systems at sites across the US. These systems represent the first focused attempt to install the best collector technologies, component hardware, and systems available at the time. As a result of that effort, nearly 350 kW of flat-plate, grid-tied photovoltaic systems,[4] both roof and ground mounted, were installed at an average price of $30.00/W in 1980 dollars. It is interesting to note that of the $30.00/W, $10.00/W was for modules, and the remaining $20.00/W accounted for balance of plant costs including site preparation, foundations, structures, wiring and system protection, inverters, and engineering. A 300-kW system[5] installed by the City of Austin (Texas) Municipal Utility in 1986 and a 570-kW system[6] installed at Kerman, California by Pacific Gas and Electric in 1992, both using the same type of hardware and installed by the same company, provide meaningful cost data points for the historical progression of

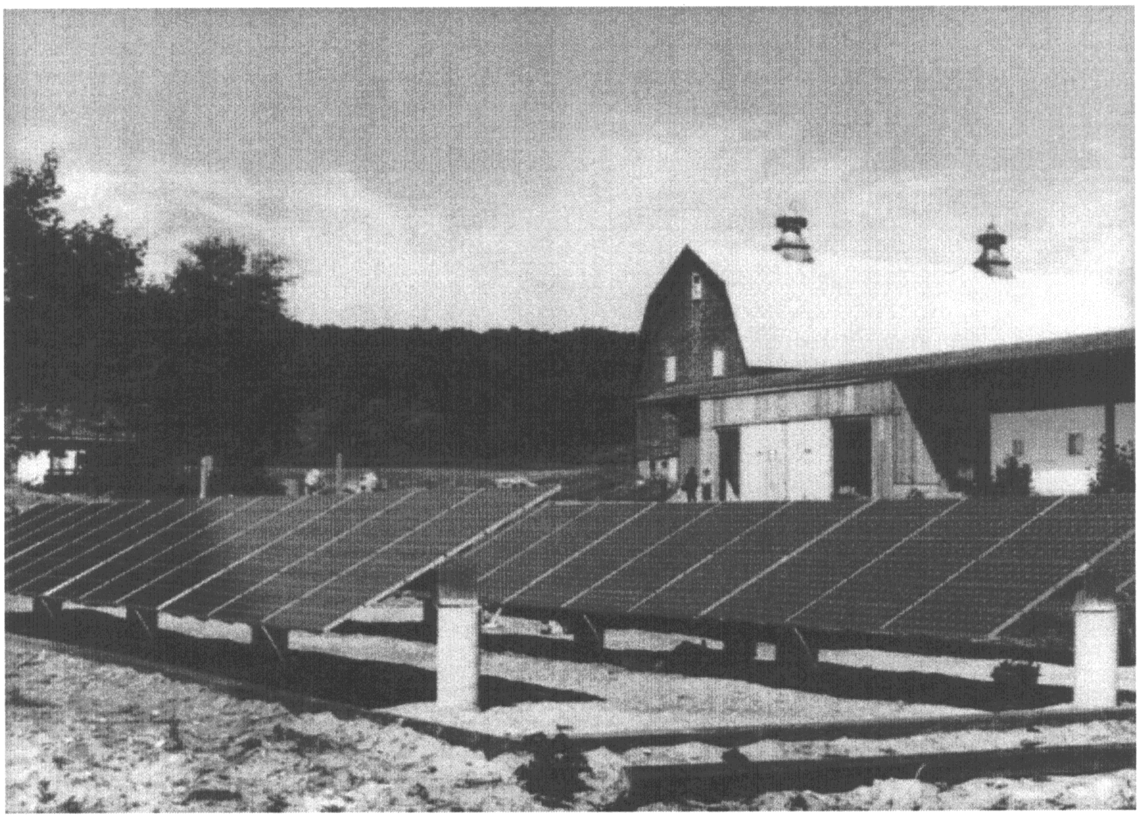

Figure 2. Hybrid photovoltaic system at North Manitou Island

photovoltaic systems. The cost of the Austin system ($10.55/W in 1986 dollars) is $8.02/W in 1980 dollars, while the cost of the Kerman system ($7.81/W in 1992 dollars) Is $4.15/W in real 1980 dollars. Costs of $6.00/W for large grid-tied systems in 1998 have dropped to about $3.00/W in the same 1980 dollars. In light of this 10-fold drop in real system costs to date, what is to be expected for future system prices? Let us examine a grid-tied system selling today at $6.00/W in current-year dollars. Note that the conversion from current to real dollars assumes a 4% average annual increase in the inflation rate for durable goods. A comparison of the system cost components between 1980 and 1998 is shown in Table III.

It is interesting to note that although the total system cost and balance of plant costs have been reduced in real dollars by an order of magnitude, the module costs have seen only half that reduction. Although these reductions have been impressive, it is unlikely that reductions of the same order of magnitude can be attained in the future.

With the lower costs of today's modules and balance of plant, it is important to look at what further reductions are possible. The total amount of photovoltaic module shipments in the world in 1997 was reported[7] to be approximately 130 MW. The photovoltaic production capacity has been growing at a long-term annual rate of 15–16% and has resulted in a doubling of the capacity in just the last 4–5 years. This

Table III. Comparison of costs for 1980 and 1998 systems

Cost component	1980 System (1980 $/W)	1998 System (1998 $/W)	1998 System (1980 $/W)
Modules	10·00	3·50	1·73
Balance of plant	20·00	2·50	1·23
Total System	30·00	6·00	2·96

rate of increased capacity has been sustained for some time, dating back to the early 1980s when total worldwide production was less than 15 MW; if it remains relatively constant, worldwide production should reach the 1 GW level by 2010. Progress over the past 15 years shows that it has taken a factor of between 2 and 3 increases in system capacity to reduce real system prices of large, commercial-size systems by one-half. This is a much more accelerated cost reduction as a result of growth than with other high technology industries that show 1–2 orders of magnitude increase resulting in a halving of the costs.[8] This photovoltaic experience is confirmed by a recent study[9] that indicates an increase in manufacturing capacity by only a factor of three coupled with production process improvements will decrease module manufacturing costs for crystalline silicon from today's costs to $1.20/W. But what is to be expected for tomorrow's systems?

Crystalline silicon modules continue to dominate the marketplace, although the role of thin films has been increasing. The market challenges for thin-film technologies were discussed in a recent article by Little and Nowlan.[10] In that article, the authors developed a benchmark module production cost of $1.78/W for crystalline silicon against which other lower efficiency collectors, such as amorphous silicon, can be compared. To examine collector cost impacts on systems, we have extended these manufacturing cost arguments to a full system cost comparison for grid-tied systems of comparable power. It should be noted that others have chosen to make this type of comparison by using parametric variations with collector efficiency as one variable. We, on the other hand, have chosen to make this a discrete comparison, noting that there have been only small increases in efficiencies for commercially available collectors over the past 5–10 years. A 12% crystalline silicon module and a 6% amorphous silicon module, representative of today's commercially available collectors, are compared in the following tables. Note that area-related costs include array field components such as site preparation, structures, foundations, wiring, and installation labor that depend on array size. Fixed costs include design, engineering, interest during construction and other indirect costs, as well as system costs such as permits and other costs that are not dependent on array size. Our experience indicates that fixed costs are typically 10% of the total system cost for mature system designs. Table IV shows that the amorphous silicon module must cost less than $1.11/W to compete at a system cost of $3.00/W.

The effect of collector efficiency on area-related costs will present a major challenge for future thin-film systems. Even for today's systems, the 2:1 module efficiency advantage between commercial crystalline and amorphous silicon collectors creates a difficult situation for system cost parity. As shown in Table V,

Table IV. Comparative projected system costs for crystalline and amorphous silicon collectors

System component	Crystalline silicon ($/W)	Amorphous silicon ($/W)
Modules	1·78	1·11
Area related	0·67	1·34
Fixed	0·30	0·30
Inverter	0·25	0·25
Total system	3·00	3·00

Table V. Comparative costs for today's crystalline and amorphous silicon systems

System component	Crystalline silicon ($/W)	Amorphous silicon ($/W)
Modules	3·50	2·10
Area related	1·40	2·80
Fixed	0·60	0·60
Inverter	0·50	0·50
Total system	6·00	6·00

today's amorphous silicon modules must cost less than \$2.10/W to compete at today's system prices of \$6.00/W.

Two inferences can be drawn from this information. First, the US industry has indicated that it believes that \$1.78/W and less can be realized for crystalline silicon modules, resulting in large part from an increase in manufacturing capacity. Second, other lower efficiency modules will not only have to be less expensive on a dollar-per-watt basis to compete with crystalline silicon, but there will also have to be substantial reductions in area-related costs for both technologies to achieve lower system costs. As commercially available thin-film collector efficiencies increase, the disparity in area-related costs will diminish. A major challenge to tomorrow's grid-tied photovoltaic systems are creative designs and installation techniques that reduce today's area-related costs, such as reduced piece parts, minimal site preparation, and use of standard components.

Cost reduction for hybrid photovoltaic systems presents an even greater challenge. Collector costs in remote power systems are typically 25% or less of the overall installed cost. A substantial portion of remote-system costs deals with batteries, battery chargers and engines that can be treated almost like fixed costs because they have not experienced any significant price reductions in years. Small improvements in collector efficiency and/or module cost reductions are not likely to significantly reduce system costs.

WHAT ARE THE BASICS OF SYSTEM PERFORMANCE AND DESIGN?

Generally, the ability to understand and predict the performance of photovoltaic systems is not yet where it needs to be. Although very accurate predictive models do exist, the input data have to be deciphered first, starting with the collectors themselves. There are differences between manufacturers' module performance specifications that are based upon laboratory testing and data collected from outdoor testing. A set of data[11] available from the Florida Solar Energy Center indicates that module power ratings determined from field tests for a wide variety of commercially available modules are typically $5-20\%$ lower than the manufacturer-specified rating. These discrepancies are by no means limited to modules, but extend to other components as well.

Modules are generally advertised and sold on a dollar-per-watt basis at some standard rating, typically standard test conditions (STC) of 1000 W/m^2, air mass 1·5, and 25°C module temperature. These rating conditions are only occasionally met in the field, so other means of predicting output must be used. One method is to apply derate values that account for field losses to the aggregate module dc power to obtain an ac rating for the system. Let us look at what we get when we follow the process, as shown in Table VI. The product of the loss multipliers is 0·65, resulting in a derate of 0·35. For a system with an aggregate dc module rating of 10 kW, based on manufacturer specification, the total system ac derate is 3·5 kW, giving an average annual ac rating of 6·5 kW. This simple process provides an amazingly accurate rule of thumb for actual power output, especially when combined with actual field power ratings of the modules.

The procedure is complicated when one attempts to rate a hybrid system based upon its photovoltaic rating alone. For example, a recently installed system at Dangling Rope Marine in Glen Canyon National Recreation Area, Utah (Figure 3) has two 300-kW engines, a 115-kW array (aggregate modules), and 2 MWh of battery storage. The photovoltaic array produces about one-third of the on-site energy requirement. Referring to this as powered by a 115-kW photovoltaic system is misleading. A better way to refer to a hybrid system is to use its daily energy consumption. In this case, the Dangling Rope power

Table VI. Simplified system derating method

Loss mechanism	Variable	Loss multiplier
Weighted average operating temperature	+30°C	0·85
Soiling, mismatch and inverter losses	−10%	0·9
Weighted annual insolation	−150 W/m^2	0·85

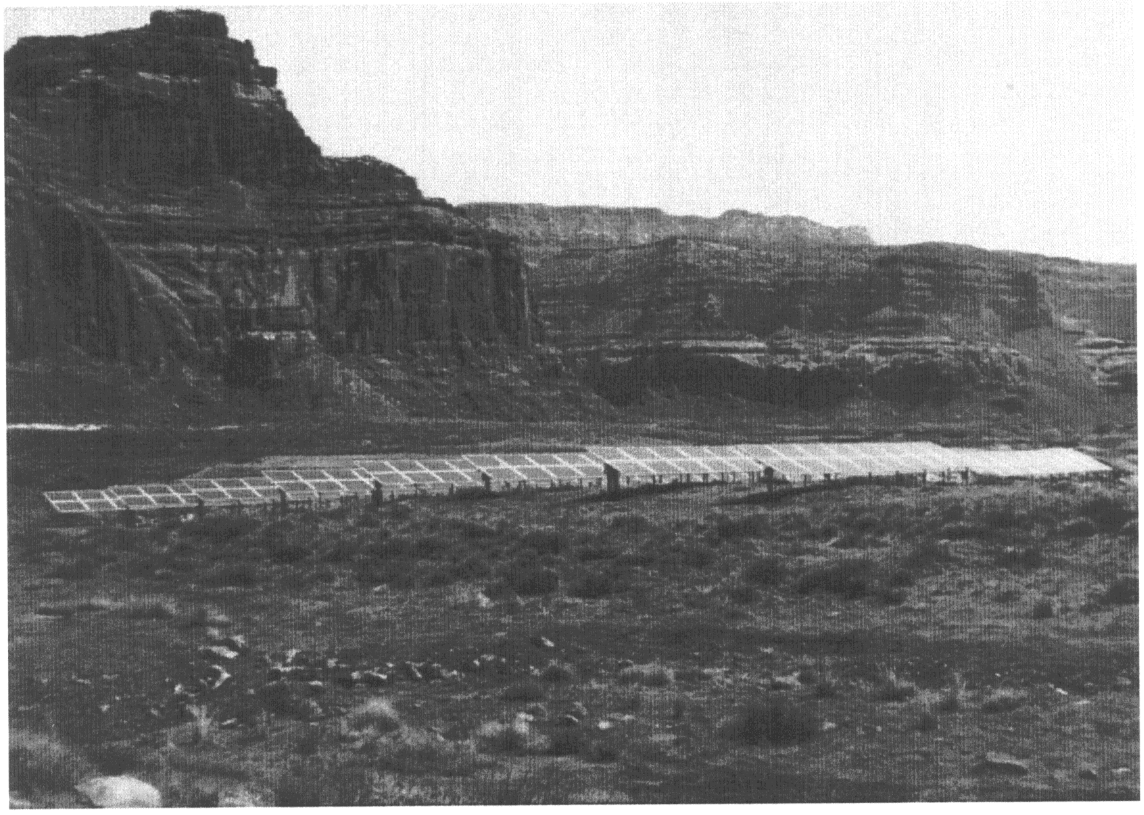

Figure 3. Hybrid photovoltaic system at Dangling Rope Marina, one of the largest hybrid systems in the U.S.

system would be better described as a 750-kWh/day-hybrid system. Another more difficult concept when analyzing photovoltaic systems is how to factor in array utilization. When the array output exceeds the load and the battery is fully charged, any generated power is discarded or not generated. This can be as high as 30% in the summer in some remote power systems designed to operate year round. This will not affect the rating of the system but will have an impact on the energy output.

One element of photovoltaic system design is determination of the solar resource; i.e., the amount of solar insolation available at a site. Consequently, there have been efforts to measure and define the solar resource throughout the world, and many statistical treatments of the data have been developed. Although insolation has an impact on the design, performance, and value of photovoltaic systems, it is by no means the only critical parameter.

Photovoltaic systems are said to be modular, because the basic building block of an array is a module. Modules are rated in peak watts, and typically vary between 50 and 300 W for today's commercially available terrestrial power modules. One can imagine that almost any power level can be developed from such small increments. However, for most cost-effective systems today, the photovoltaic array is simply a battery charger, and its power rating is not the key to the system design and performance. Meeting the load predictably is. Modularity means that a photovoltaic system can be sized to match the load closely, and that it can be expanded or decreased in the future if the load changes.

We find that the key technical factors to system design for stand-alone systems are photovoltaic array output-to-load ratio and load-to-battery capacity ratio (often referred to as days of storage). The importance of output-to-load ratio reflects that the power system has to provide 100% of the on-site electricity load. It is this load that is the primary independent variable (along with insolation) in system design. In most cases, the first duty of a system designer is to attempt to reduce or levelize the load. The size of the load and the required system availability dictate the amount of directly usable energy or energy storage that is required. This energy requirement, combined with insolation data and desired availability, then allows the photovoltaic array size to be selected. An example brings these issues into perspective.

A photovoltaic-powered livestock water pumping system requires storage in the form of a water tank or reservoir. By over-sizing the pump-motor set, the system can provide all of the pumping during the daytime hours. The design is driven by the requirement of daily water usage. The tank size (storage) is set by how many days the system may not operate because of low solar insolation. Then the pump-motor is chosen and the array is matched to that electrical load. When water storage is replaced by electrical energy storage, say to meet a 24-hour-a-day load, the process remains the same; the only difference is that batteries replace water.

Many packaged photovoltaic systems are designed with the erroneous concept that the energy produced by the photovoltaics should match the load. The ratio of daily array generation-to-load is usually about 1:1 in many small lighting systems; such a system usually has severe operational limitations. Experience shows us that a ratio between 1·5:1 and 2:1 is much better if trouble-free operation and predictable maintenance are desired. This approach, however, is more expensive on a first-cost basis. More useful is the ratio of usable energy storage to daily load. Experience[12] has shown us that limiting the amount of battery capacity discharge on a daily basis to no more than 15% provides system availability in the 99% range even with a daily generation-to-load ratio of only 1:1. Under anything other than bright sky conditions, such as in the wintry central US, this ratio must be increased. On the other hand, when one employs typical design guidance that uses long-term averages for determining battery sizes for the northern and eastern parts of the US, where weather patterns may be of long duration, the availability of the system drops significantly because of 'seasonal derate' a term used to describe the choice to allow the energy storage subsystem to work at a deficit over a long period of time, such as the winter months when solar resource is at its lowest. This is very common in packaged systems and may result in reduced availabilities and shortened battery life.

HOW LONG DOES A PHOTOVOLTAIC SYSTEM WORK?

A common design goal for photovoltaic power systems in the US is to meet the demands of the electrical loads predictably for 30 years. Because the performance of all of the system components changes over the expected lifetime, designers use several different approaches to reach this goal. Terrestrial photovoltaic systems have been in use for approximately 20 years, since the late 1970s. Figure 4 shows the 18-year-old hybrid photovoltaic system at Natural Bridges National Monument, Utah, the oldest hybrid system still operating in the US. The components used in the early systems were not 30-year lifetime components. As a result, the photovoltaic community has very little long-term performance data to corroborate the anticipated 30-year life. The answer to system lifetime can be examined from various points of view.

Module warranties tend to mislead all but the informed buyer. A 20-year warranty allays many fears that a photovoltaic module will not perform as advertised. In fact, experience shows that crystalline modules will produce power for a long time. The warranties, however, are of limited use. First, recurring costs in photovoltaic systems are quite low if no warranty service is required and if none of the hardware has to be replaced. These costs are usually less than 5% of the life-cycle cost of the system. However, when a component fails, even under warranty, the cost associated with finding and replacing the failed element, crating and shipping, and re-installing when the replacement is returned is not covered by the warranty. In fact, the cost to perform this action on an individual battery, module, or other component usually exceeds the value of the item.

The useful life of batteries in photovoltaic systems is usually between 3 and 9 years, depending on use. The batteries will probably need to be replaced several times, the loads will undoubtedly be replaced or repaired many times, and the power electronic components will probably be replaced at least once over a 20-year period. Experience[13] has shown that these capital replacement costs are 15–20% of the initial capital costs.

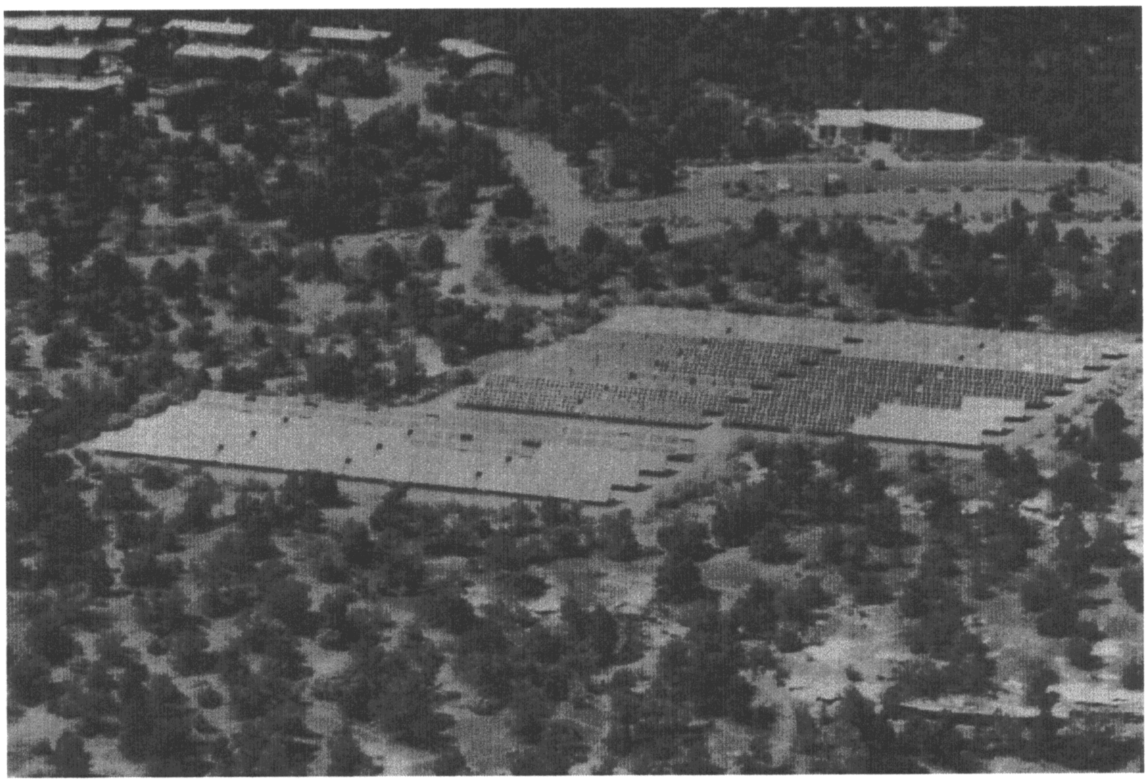

Figure 4. Natural Bridges hybrid photovoltaic system

Power conditioning hardware and controls are the source of many of the life-limitations of a system. Our experience indicates that as much as 80% of recurring costs are related to the power handling subsystem, due to poor reliability.

The long-term life of large grid-tied systems installed during the 1980s in the US has not been positive. Most of these systems are no longer operational.[14] All of these systems were installed as experiments and were never intended to be cost effective. In many cases, the owners chose to dismantle the systems and sell the components as soon as significant maintenance was required. This experience certainly raises issues about the impact of technology demonstrations; but the health of the secondary market for photovoltaic products is testimony to the inherent worth, reuse, and reapplication of photovoltaic systems.

Degradation of system components occurs in modules as well as balance of plant.[15] The amount of degradation is a function of the component and the environment in which it operates. Lead-acid batteries lose half of their cycle life for every 10°C increase in average operating temperature over 25°C. Most batteries in stand-alone photovoltaic systems eventually fail due to stratification and sulfation consistent with undercharged operation. The batteries in hybrid systems, on the other hand, show significant aging because of corrosion caused by the high rates of charge that can be produced by the engine generators. Today's crystalline silicon modules degrade at reasonably slow, but measurable, rates of less than 1%/year which is a decrease from 1–2%/year seen for modules manufactured in the mid-to-late 1980s. Power handling equipment and controls are standard solid-state electronic devices and probably have a service life of 10–15 years. Warranties for these items currently range from 90 days to 2 years. Everything, from structures to wiring to switchgear, has some rate of degradation.

The real issue of system lifetime is the cost associated with maintenance; those issues are tackled in the next section. When recurring costs become too high, many system owners discontinue operation; how long that takes is still not established.

WHAT MUST BE DONE TO MAINTAIN A PHOTOVOLTAIC SYSTEM?

System and component reliability and service lifetimes go hand in hand with maintenance requirements and cost. A photovoltaic system requires little maintenance unless one of the components needs to be replaced. The maintenance areas in photovoltaic systems are usually the inverter and/or controls and the battery subsystem. We begin with results from three studies.

Detailed performance and economic analyses[13] on recently installed hybrid systems indicate the relative importance of capital replacement costs in stand-alone systems. Three photovoltaic hybrid systems were selected for review because they represent three distinct types of remote electrical loads: large mini-grid or village power systems, single residential or commercial sites, and telecommunications repeaters. The three photovoltaic hybrids selected for analysis were (1) a large 115-kW power system (Figure 3) at Dangling Rope Marina, Utah; (2) a small 9·6-kW power system (Figure 5) at the Chaparral visitor area in Pinnacles National Monument, California; and (3) a 12·8-kW telecommunications system (Figure 6) at Rogers Peak, in Death Valley National Park, California.

The performance of each hybrid system was documented and the 20-year life-cycle cost (LCC) was calculated. A comparison of the results is provided in Table VII. Of particular importance is the value of the recurring cost as a fraction of the overall net present value (NPV) of the life-cycle cost. While recurring maintenance costs are limited to about 5%, the overall recurring costs (maintenance plus capital replacement) run as high as 25%. These points are usually not stressed in a presentation of photovoltaic systems, but their magnitude makes them a major issue in evaluating any system of this type.

The maintenance required for stand-alone photovoltaic systems in the range of tens to hundreds of watts, such as the campground host system shown in Figure 7, is small on a per-system basis. The economics of the systems is extremely sensitive to maintenance because there is so little energy produced.

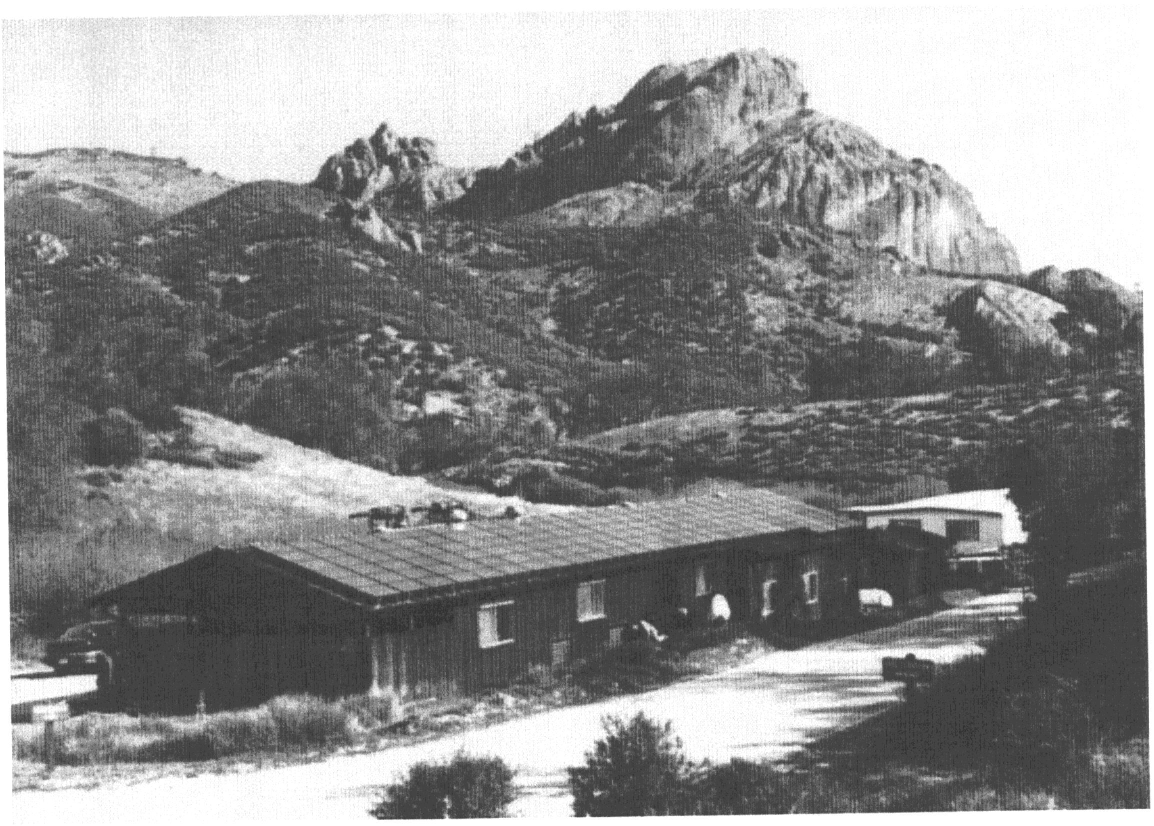

Figure 5. Photovoltaic system at Chaparral

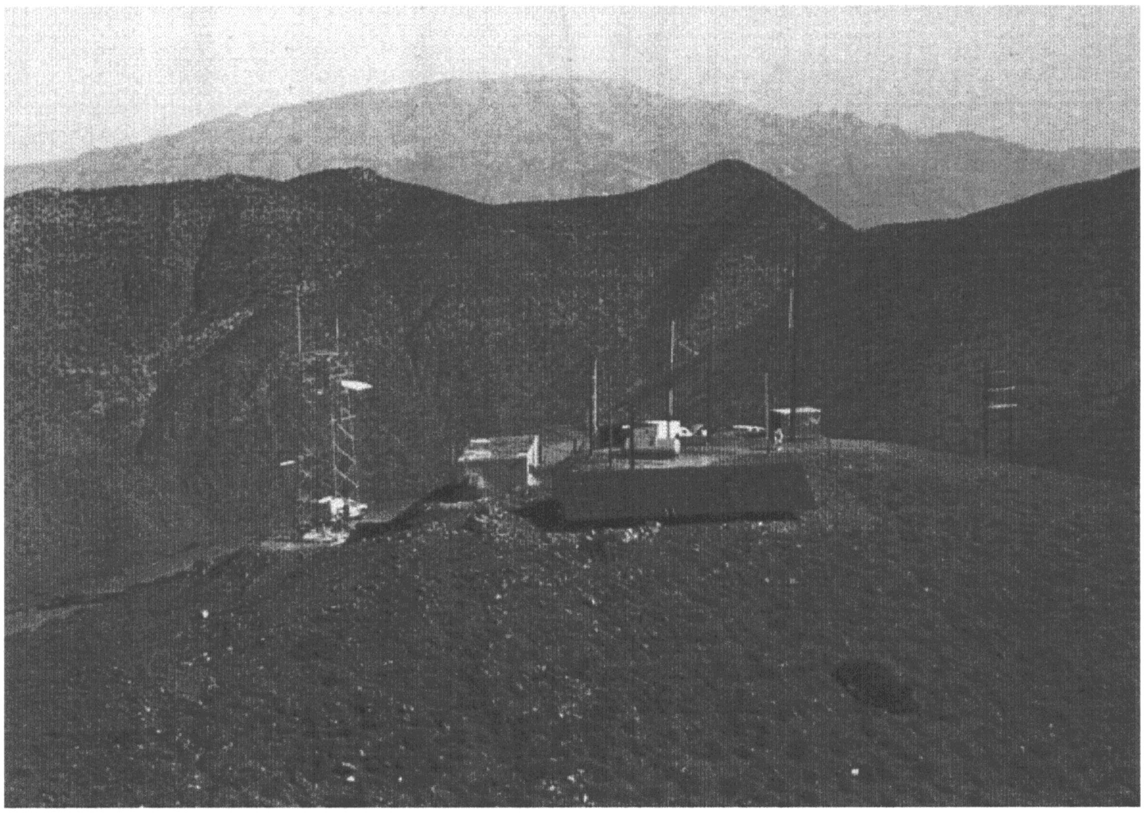

Figure 6. Photovoltaic system at Rogers Peak

Table VII. Life-cycle cost comparison of three hybrid systems

Costs ($1000)	Dangling Rope		Pinnacles		Rogers Peak	
	Engine only	Hybrid	Engine only	Hybrid	Engine only	Hybrid
Initial capital	87	1300	24	135	24	287
Recurring maintenance	394	190	74	10	195	10
Fuel	2337	1198	165	22	144	8
Capital replacement	164	201	32	44	45	47
NPV	2981	2890	295	211	408	352

A recent study[16] of over 70 systems, mainly lights, used in the Colorado State Parks indicated that 60% of the maintenance cost was associated with vandalism. Clearly this is unscheduled maintenance. Scheduled maintenance of small systems includes battery replacement, replacement of charge controllers, light ballasts, and inverters. The one-year cost for maintenance and capital replacement per system, including vandalism, was reported at approximately 15% of the initial system cost. Excluding vandalism, this number drops to 7%.

Maintenance and reliability information[17] from two separate sources for grid-tied systems presents a mixed story (Table VIII). The data come from four phases of 332 systems installed by the Sacramento Municipal Utility District (SMUD) from 1993 through 1995 and from another 108 systems cost shared by the US Environmental Protection Agency (EPA) throughout the country and monitored from 1993 to 1996 by Ascension Technology for the UPVG. The systems contained similar hardware and quality of

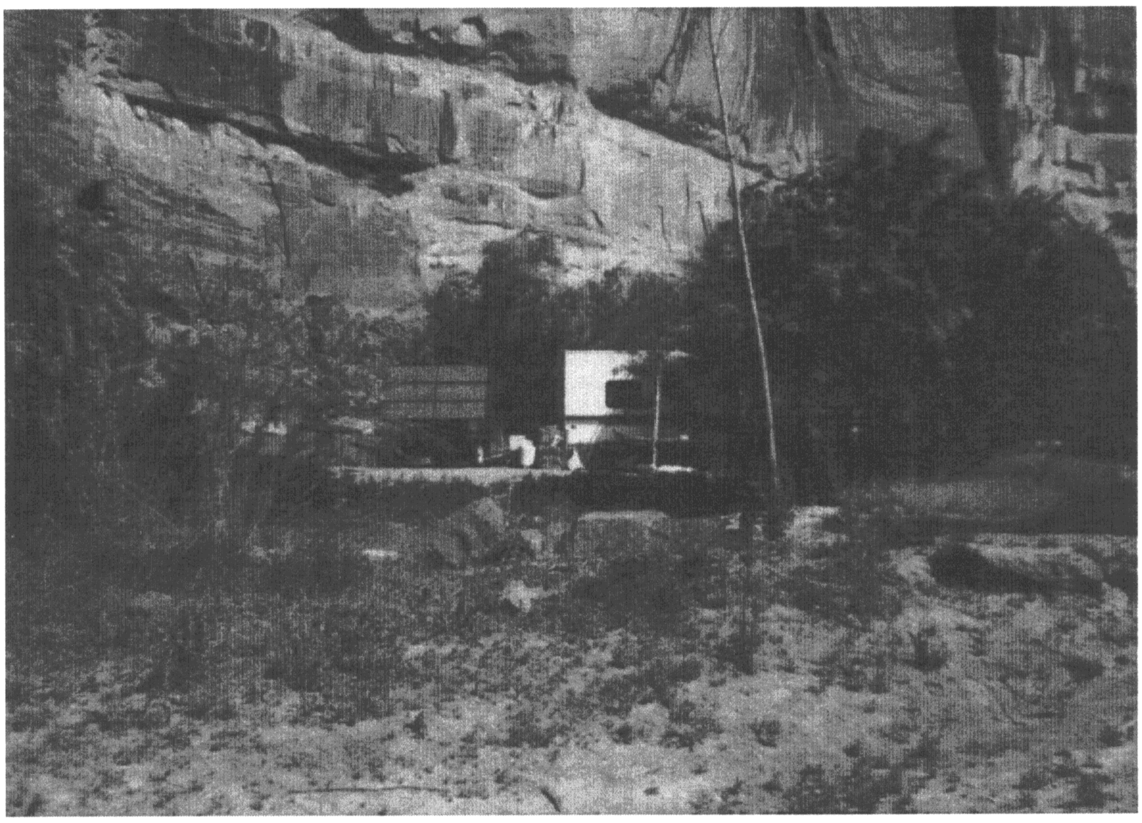

Figure 7. Small stand-alone photovoltaic system that provides power to a campground host, typical of recreational applications in the U.S.

Table VIII. Reliability and maintenance for grid-tied systems in 1997

	SMUD Pioneer 93	SMUD Pioneer 94	SMUD Placer 95	SMUD RMI 95	EPA 1993
MTBF (years)	7·0	15·8	11·2	16·2	1·2
MTTR (days)	216	78	108	173	19
Availability (%)	86·4	98·3	88·8	83·5	91·9
Maintenance ($/kWh)	0·021	0·004	0·042	0·035	0·095

installation, yet the results vary widely, as shown above. Note that MTBF refers to mean time between failure, MTTR refers to mean time to repair, and availability as used here is defined as the percentage of time that the systems produce energy compared to the time that they should produce energy. Most of the maintenance involved inverter repair on units that were manufactured between 1992 and 1995. The maintenance cost variations, especially for some cases where systems used the same hardware, are not easily explained. The implications for future grid-tied systems, targeting levelized energy costs of $0.08–0.10/kWh, are significant. At the high cost values shown in the table, maintenance is as expensive as the cost of electricity. At the low values, maintenance is at reasonable levels and will not be a barrier for expanded use. Clearly there is a need for more data. Maintenance is a continuing systems issue.

ARE PHOTOVOLTAIC SYSTEMS SAFE TO USE?

A photovoltaic generator presents some rather unique concerns in terms of electrical safety. With any light present, there is the potential for electrical current flow and potential shock hazard. The array itself may be mounted on a metallic structure susceptible to lightning strikes during thunderstorms. In particular, in the US, photovoltaic arrays are protected from surges and grounded to avoid personnel hazards and equipment damage due to surges during electrical storms. There are other safety concerns about power distribution, energy storage, etc., but these are not unique to photovoltaic systems.

In addition to concerns related to shock, there are additional concerns about fire safety, especially when the systems are tied to dwellings or other structures. For these reasons, most installations of photovoltaic systems in the US today follow the National Electrical Code (NEC), which has been sponsored by the National Fire Protection Association since 1911 and is embodied in every local building code throughout the country. The NEC states that adherence to the recommendations made will reduce the hazards associated with electrical installations, but that the recommendations may not lead to improvements in efficiency, convenience, or adequacy for good service. Probably the most important aspect of the NEC is that it is used during the inspection of electrical systems after their installation. This review provides an additional level of quality control for installed electrical systems of any type.

In parallel with the NEC, many of the specifications for photovoltaic systems require testing and listing by an approved testing laboratory like Underwriters Laboratories, Factory Mutual Research Laboratories, Inc., or ETL Testing Laboratories, Inc. The use of listed components and good engineering practices (electrical, mechanical and structural), following the NEC, and safety recommendations in appropriate standards[18] reduce the probability of damage to equipment or hazards to personnel safety. The authors know of no loss of life or loss of buildings because of photovoltaic systems in the US or elsewhere and believe that the use of codes and standards has largely been responsible for this safety record. There have been a number of fires in large array fields, catastrophic inverter failures, and arcing and fires associated with large, high-voltage battery banks. However, in each of these cases, the problems were associated with non-compliance with appropriate codes and standards.

HOW DOES PHOTOVOLTAICS WORK IN HYBRID SYSTEMS?

The most common power option for remote residences, facilities, and other electrical loads are engine generators, most commonly powered by diesel fuel. Over the past 20 years, many extremely remote sites with limited and costly site access for maintenance and fuel delivery have had their engine-based power systems modified to hybrid photovoltaic systems. Remote radio repeater and telecommunication sites are examples where hybrid systems are the preferred option. The reasons are simple. The typical diesel engine-generator based system requires regular oil and filter changes (every 250 hours of operation or so) and provides anywhere from 2 to 11 kWh per gallon of fuel used, depending on how well the generator is matched to the load. The cost of travel to and from the site to perform maintenance is restricted during certain times of the year and can be more expensive than the actual maintenance itself. For these sites, almost all the life-cycle cost of the power system is due to fuel and maintenance.

The original hybrid systems replaced the engine with a photovoltaic array as their primary power source. Because of the need for 24-hour operation, secondary batteries were added to the systems and the engines were used as back-up power generators. Typical designs were driven by such factors as allowable fuel storage and engine run time. The economics and/or allowable costs of the photovoltaics were based simply on the life-cycle savings derived from nearly eliminating the costs for site access to deliver fuel and perform engine maintenance. Most of these hybrid systems used highly reliable conventional battery chargers and rectifiers with simple controls to meet dc communication loads.

In the early 1980s, another potential market for hybrids began developing, namely for engine augmentation, typically to meet an ac load. Here the system designs were focused on optimizing the performance of the engine generator, which was not well matched to the load and was operating inefficiently. This situation occurred for a number of possible reasons, including wide variations in the daily electrical load as well as the seasonal load. The hybrid modifications were based on the assumption that the addition of a power processing subsystem (PPS) with battery storage could improve generator performance by allowing the generator to run at greater efficiency for shorter periods of time. This approach has in fact worked successfully[19] in many areas of the world. The addition of the PPS and battery storage result in an increase in the load because of inefficiencies of both components. These load increases range from 15% to more than 45%[13] with smaller increases as the engine runs more. With this approach, the engine run time can easily be reduced by one-half or more and fuel use by two-thirds. These improvements can provide simple payback periods of less than 10 years.

The addition of photovoltaics to these systems, however, is questionable from a strictly economic point of view. We have been unable to document a hybrid system of this type where the addition of photovoltaics has a clear, positive economic benefit, even though we have conducted detailed evaluations of more than a dozen hybrid systems from residential to large facility applications. These systems may appear to be economic relative to an engine-only option that is poorly matched to the load. However, when compared to the engine/PPS/battery systems, the addition of photovoltaics is usually not economically viable. Any apparent economic benefit from photovoltaics occurs because the savings from the improved efficiency of the engine obtained from the addition of the PPS and batteries are used to offset the costs of the photovoltaics. To understand this, one must first realize that a system with a PPS and batteries has already been designed to allow the engine to operate at its maximum efficiency. The energy from the photovoltaics must then compete with the energy from the engine at its most efficient operation. For very remote sites with high fuel delivery and maintenance access costs, photovoltaics is competitive. For sites with lower fuel and maintenance access costs, the energy cost from the diesel-powered engine generator is usually less than \$0.30/kWh. The requirement that photovoltaics provides power at the same or lower cost as a fully loaded engine generator at the same location is a significant economic challenge for today's systems. Other considerations, such as the cost of emissions, avoidance of fuel spills, and noise abatement do add considerable value to photovoltaic hybrids and in many cases these reasons, not generation costs, will justify the use of photovoltaics.

In summary, the use of hybrids where photovoltaics essentially replaces an engine as the prime source of power production at very remote sites is a well-established technology throughout the world. In addition, the operating efficiency of some engine-based power systems can be improved and economically justified by the addition of a PPS and batteries when the generator is otherwise poorly matched to the load. Although the addition of photovoltaics to these systems is technically feasible, we have no clear evidence that this option improves system efficiency or system economics. The challenge for the hybrid system designer is to develop alternative operating and design strategies that will result in a positive economic benefit from photovoltaics.

HOW DO CUSTOMERS FEEL ABOUT THEIR SYSTEMS AND WHAT IS NEEDED FOR MORE SYSTEMS TO BE PURCHASED?

A recently completed US Department of Energy program to expand photovoltaics use within the federal sector sheds some light on customer acceptance of photovoltaic systems. The Renew the Government program developed partnerships with three federal agencies — the National Park Service, the Bureau of Land Management, and the Forest Service — to establish sustainable use of photovoltaic power systems throughout each agency. Together these agencies have jurisdiction over 25% of the land area in the US, much of it remote, with significant opportunities for high-value stand-alone and hybrid photovoltaic systems. A comprehensive survey[20–22] was conducted within each agency to assess the current use of photovoltaics and to determine the level of acceptance of photovoltaic systems. The combined results showed that 97% of system owners were satisfied that the system met the design objectives.

The surveys identified cost and lack of familiarity with photovoltaics as the most important barriers to expanded agency use. To address agency familiarity, over 125 pilot systems in excess of 300 kW were

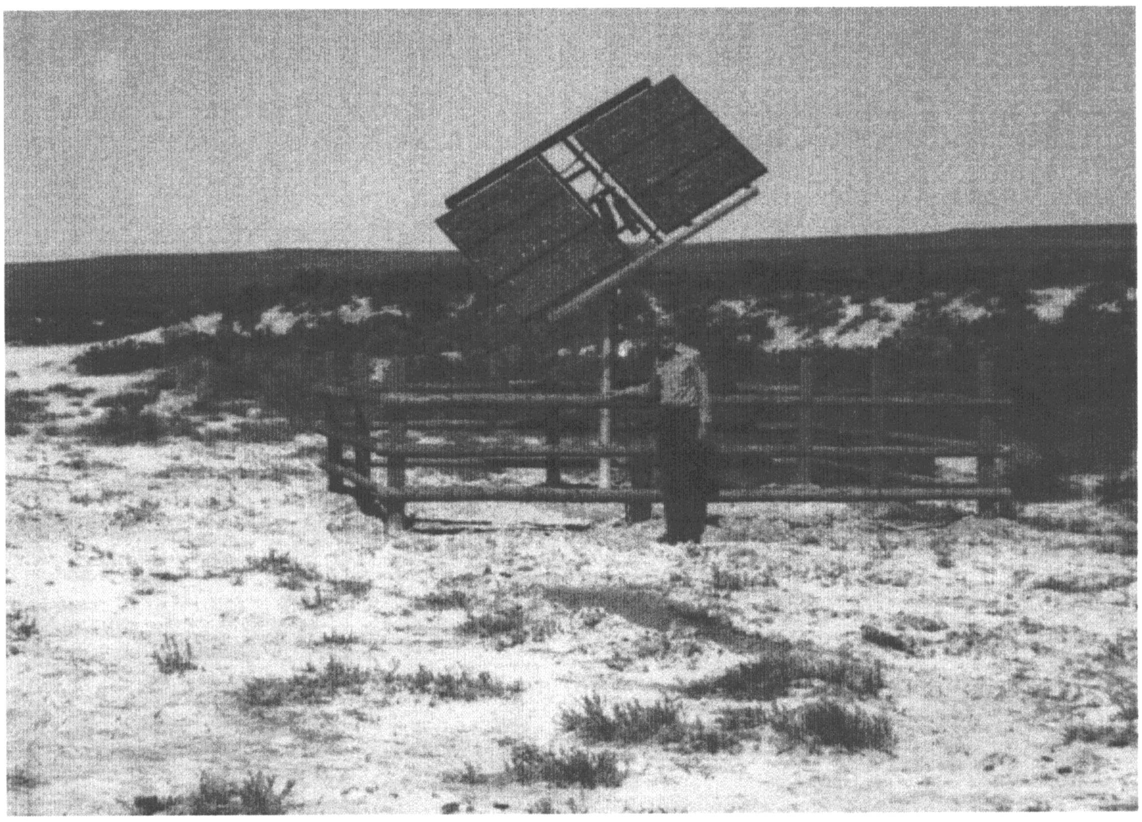

Figure 8. Photovoltaic water pumping system, identified as a major opportunity for expanded applications within the Bureau of Land Management

deployed across the US over the past four years. The primary applications—facility power, water pumping, and lighting—were determined based on extensive surveys of future agency power needs (see Figure 8 for an example).

Familiarizing agency personnel through education, system procurement, and system installation is the best way to overcome this barrier. The lessons learned[23] through this program are equally applicable to a utility, an architectural/engineering firm, a small business, or a homeowner. Table IX presents a number of the lessons learned. Note that a number of these lessons are specific to agency processes, such as

Table IX. Lessons learned to increase customer familiarization with photovoltaic systems

- Determine what you need before you procure it;
- A project advocate for photovoltaics use must exist in the agency and must be in a position to affect decisions;
- A system should be designed and adequately specified before it is procured, and the agency should be directly involved;
- The procurement of standardized photovoltaic systems through standardized specifications and standardized processes greatly benefits the agency;
- Packaged procurements of standardized systems for multiple agency sites through a centralized office have proven successful;
- Human presence, such as a site host with a photovoltaic power system, is an effective way to prevent theft and other vandalism at a remote site;
- The cost of battery replacement in photovoltaic systems must be included in planning for future maintenance costs for the system;
- Successful projects are those that are based on best value, such as environmental concerns, energy security, educational opportunities, lowest user investment and lowest life-cycle costs;
- Viable photovoltaic projects are typically for remote applications where the cost of photovoltaics is compared against other remote power options; and
- Energy savings cannot be used to justify the photovoltaic project costs.

procurement and installation, whereas others are relevant to photovoltaic systems in general, such as design, maintenance, and cost.

Experience with federal agencies indicates that extended warranties and long-term service maintenance contracts are the best ways to assure system owners that systems will perform as expected. This puts the burden of quality control and performance on the system supplier. System certification is another option to overcoming the customer familiarization gap. Some have proposed[24] that a complete system certification, endorsed by the photovoltaics industry and the buyer community, would avoid issues associated with verifying design procedure, installation procedure, performance of the power processing hardware, system rating and the like. Such certification would address safety and performance, as well as a product quality and inspection program. It should be noted that a great deal of activity is being directed toward the development of tests[25] and standards[26] for system certification programs in the US as well as elsewhere in the world.

CONCLUSION

The use of photovoltaic power system technology continues to increase in the US especially for the remote power system market. The technology and infrastructure have advanced, and the status is described below.

How much do photovoltaic systems cost?

The cost of photovoltaic systems has been reduced by an order of magnitude over the last two decades and is now close to being cost competitive with grid-tied electricity in the US, with installed costs as low as $5.07/W at one site. Stand-alone system costs are higher and range from approximately $10.00/W to over $20.00/W.

What might happen to system costs in the future?

Module costs below $2.00/W are expected within the foreseeable future for crystalline silicon and thin films. Area-related costs must be reduced for tomorrow's systems to achieve $3.00/W cost goals.

What are the basics of system performance and design?

System performance is often lower than predicted because of bad design, poor selection of system components, and inappropriate component ratings.

How long does a photovoltaic system work?

There has been little documentation on lifetimes, from a technical point of view, for terrestrial photovoltaic systems. Long-lived systems do require maintenance and parts replacement; but as long as the system owner wishes to continue to operate the system, we know of no limit to possible system lifetime.

What must be done to maintain a photovoltaic system?

Recurring system costs, including maintenance and capital replacement, vary widely (nearly an order of magnitude in the few published reports available) and must have better documentation in the future. Current published reports on grid-tied systems show maintenance costs vary from about $0.01/kWh to as high as $0.10/kWh. Maintenance for stand-alone systems is relatively small, 5%, but capital replacement can be as much as 20% of the life-cycle cost for hybrid systems.

Are photovoltaic systems safe to use?

These systems are safe. Following national codes for fire safety and standards for good engineering have led to an impeccable safety record in the US.

How does photovoltaics work in hybrid systems?

Hybrid systems, where photovoltaics essentially replaces an engine as the prime source of power generation for very remote sites, are economically viable and a well-established technology throughout the world. The efficiency of some engine-based power systems can be improved by the cost-effective addition of a PPS and batteries when the generator is otherwise poorly matched to the load. So far, the addition of photovoltaics to these systems has not demonstrated a clear economic benefit, but does provide other value to the system owner.

How do customers feel about their systems and what is needed for more systems to be purchased?

Customer satisfaction with the technology is extremely high. Published surveys indicate that the satisfaction rate exceeds 95%, but that lack of familiarization and experience with the technology is still an issue. Standards and certification activities are addressing product performance concerns.

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